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## Strain rate dependent flow stress characterization using piezo-actuated micropress

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### Abstract

The effect of strain rate on the mechanical response during microforming deformation is investigated for commercially pure titanium and aluminum. Piezoelectric actuated micropress is used to generate controlled constant strain rate between 0.1 and 10  $\text{sec}^{-1}$  in a compression experiment using three different sizes of specimens. Investigations suggest that the increase of free and constrained surface grains results in hardening-softening competition with miniaturization. In addition, loading rate in micro compression significantly influence the work hardening behavior for both materials.

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**Keywords:** Microforming; Strain rate dependency; Size effect; Flow stress

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### 1. Introduction

Advances in miniaturization techniques have enabled new technologies in various manufacturing industries. The ever increasing demand for micro components for biomedical and energy applications continues to motivate the development of microforming technology as a methodology to create such parts in high precision and high volume. The pioneering publication in the field by Geiger et al. (2001) have garnered interest in microforming researches. Since then, there have been various investigations such as the high temperature microforming by Eichenheuller et al. (2005), the systematic classifications of size effect by Vollertsen et al. (2009), the introduction of a new material model by Keller et al. (2009) and the application of microforming specific friction investigation method by Taureza

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et al. (2014). These developments are crucial in bringing in additional knowledge to further the understanding of microforming behaviors which has been limited due to size effects.

Liang and Khan (1999) suggested that understanding of flow stress behavior over a range of strain rates is very important in metal forming and other dynamic processes. Although there have been numerous studies proposing various material constitutive models such as the model by Johnson and Cook (1985) and Zerilli and Armstrong (1987), there has not been a systematic analysis which describes mechanical response of materials under varying strain rates for small size specimens. With that regard, this paper investigates the effect of strain rate on materials' mechanical response in terms of stress-strain relation in microforming conditions through the use of piezoelectric actuated press and micro compression experiment of commercially pure titanium and aluminum.

#### Nomenclature

$\sigma$	flow stress
$\epsilon$	strain
$\dot{\epsilon}$	strain rate
$T$	temperature
$\dot{d}$	ram speed
$h_{inst.}$	Instantaneous height of specimen (for constant strain rate calculation)

## 2. Size effects and constitutive model

The adaptation of metal forming processes from conventional size to micro size has been hindered due to the size effects. Although they are only observed in miniaturized processes, these size effects are not caused by physical or chemical phenomena occurring in scaled down systems but rather they are attributed to mechanisms which increasingly become significant with miniaturization as explained by Razali and Qin (2013).

The pioneering work in microforming by Geiger et al. (2001) on miniaturization effect on mechanical response first provided evidence that there is significantly changing mechanical properties with reducing specimen size under compression. Geiger et al. (2001) showed that in a miniaturization of a cylindrical CuZn15 specimen from 4.8 mm diameter to 0.48 mm diameter, the flow stress of the material can decrease by up to 20%. This was further explained through crystal plasticity and surface layer model. In the surface layer model, it was suggested that grains next to the surface have fewer neighboring grains which impede their deformation, producing the observation of lower flow stress for these surface grains.

On the other hand, Wang et al. (2013) presented a coupled surface layer model in which the surface grains during compression of a workpiece can be declassified into free and constrained surface grains. The free surface grains are similar to the surface grains from Geiger et al. (2001) which have lower flow stress than the bulk, while the constrained surface grains have higher flow stress. This coupled surface layer model suggested that the material size effect is highly dependent on the geometry of the deforming workpiece. Material size effect observation during tension has been published by Keller et al. (2010) in which it is shown that the flow stress of the material is highly related to the number of grains across the dimension, differentiating the tension conditions between polycrystalline, multi-crystalline and quasi single crystal.

In addition, with the reduced number of grains across the dimensions through miniaturization, the workpiece isotropic mechanical property assumption is no longer valid. The small number of grains in the specimen is not enough to produce statistically isotropic overall specimen and hence the mechanical properties tend to vary between specimens. Increasing the specimen temperature during microforming deformation has suggested mixed results as Engel and Egerer (2002) found beneficial effect of temperature in reducing mechanical property variation whereas Eichenheuller et al. (2005) did not find the same effect with increased temperature.

In the conventional or large scale systems, the effects of factors such as strain, strain rate and temperature have been considered and empirically modeled. Among the established models are those by Johnson and Cook (1985)

which describes the effects of those factors as multiplication (Eq. 1) and those by Zerilli and Armstrong (1987) which considers them as summation (Eq. 2).

$$\sigma = f_1(\epsilon) f_2(\dot{\epsilon}) f_3(T), \quad (1)$$

$$\sigma = f_a(\dot{\epsilon}, T) + f_b(\epsilon). \quad (2)$$

However, the work in order to understand mechanical response in small size has been limited to only the effects of strain and size. The missing understanding on strain rate effect is highly important for design of microforming process and is of great interest.

### 3. Experiment

#### 3.1. Piezoelectric actuated micropress

In the past, metal forming and microforming have been investigated using mostly mechanical press. Mechanical presses in general have large travel movement and the addition of servo systems can provide excellent accuracy of movement as reviewed by Osakada et al. (2011). Although servo press has been a vast improvement in comparison to conventional presses with regards to speed and position control, its reliance to encoders and mechanical linkages is currently seen as a limitation for microforming applications.

The solution to this is to change the press system to one without mechanical linkages. In this study, piezoelectric actuation was used as the piezoelectric stack is capable of load bearing and the actuation movement is provided without any mechanical linkage and therefore no backlash. Using piezoelectric actuation, there is also virtually no resolution limit as the voltage bias may be provided at infinitely small increment as they are continuous parameter unlike the discrete encoder positions. The currently used actuator has been programmed with feedforward-feedback system in order to compensate for non-linearity over the travel of 200  $\mu\text{m}$ , load blocking capacity up to 5 kN and strain rate between  $10^{-4}$  and  $10 \text{ sec}^{-1}$  for use with miniature specimens.

#### 3.2. Materials and methods

The study aims to investigate the mechanical response to changing strain rate for different sizes through constant strain rate micro compression experiments. Commercially pure aluminum and titanium were selected in this study. The experimental matrix is presented in Table 1. Each parameter condition in the experiment is assigned a unique name of *xx-y-z* where the *xx* is the material type (Al or Ti), *y* and *z* are the size and strain rate identification, respectively. The specimens in the experiment were produced in cylinders with height to diameter aspect ratio of 1.25 and diameters of 2, 1 and 0.5 mm.

Table 1. Experimental matrix.

		Strain Rate ( $\text{sec}^{-1}$ )		
		0.1	1	10
Size (mm)	D0.5 H0.625	<i>xx-05-01</i>	<i>xx-05-1</i>	<i>xx-05-10</i>
	D1 H1.25	<i>xx-1-01</i>	<i>xx-1-1</i>	<i>xx-1-10</i>
	D2 H2.5	<i>xx-2-01</i>	<i>xx-2-1</i>	<i>xx-2-10</i>

Constant strain rate is prescribed by generating variable speed as presented in Eq. 3. The speed is essentially a product of the instantaneous height of the specimen and the desired strain rate. The determination of initial contact and the zero strain is one of the difficulties in the micro compression experiment. Using a mechanical press, the generic procedure is to set an initial position to a few millimeters before the specimen contacts the punch and to

apply constant head speed throughout the compression. The zero strain is then determined from the linear (elastic) portion of the loading curve.

$$\dot{d} = h_{inst} \cdot \dot{\epsilon}. \quad (3)$$

However, as the manageable stroke is very limited with the current piezoelectric press, it was imperative that the compression specimen was preloaded to a small value relative to the final loading force to ensure complete contact of the specimen with the punch. That position is set as the *experimental zero strain*. As the specimen is preloaded to 20-30 N, the measured *experimental final strain* is likely to be lower than the *true final strain* and the true stress-strain curves are shifted accordingly. The *true final strain* can be calculated based on the initial and final height of the specimen with the assumption of rigid machine structure due to the low load in micro compression. The true stress-strain curves from the repeated experiments of each condition can be fitted using regression to produce the true stress-strain curve. Illustration of this regression result is presented in the left panel of Fig. 1. Three repetitions were performed for each condition. However, the repetitions are designed to start at slightly different preload such that a wider range of true strain measurement due to the very limited machine stroke. Although in general there is larger material property variation in smaller specimen such as presented in the right panel of Fig. 1, there is not enough like-to-like repetition to suggest the magnitude of this scatter.

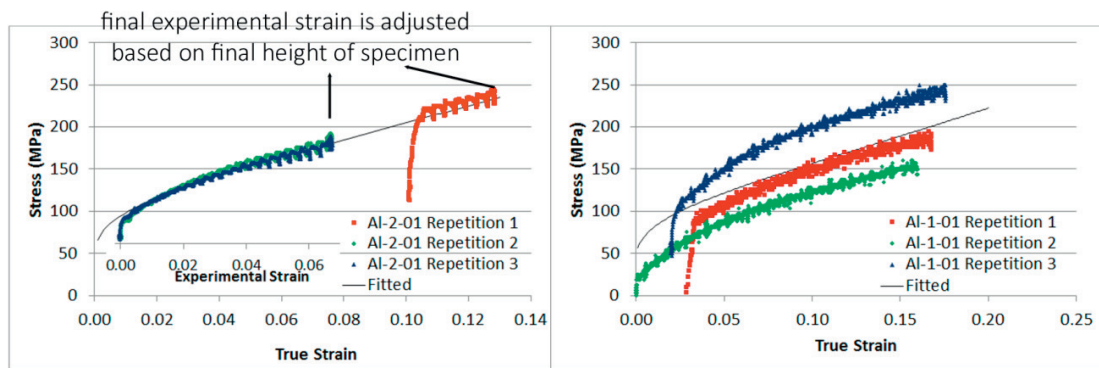


Fig. 1. Determination of stress-strain curve from three loading curves (Al-2-01) and material variation (Al-1-01).

#### 4. Results and discussion

With specimen diameter 1 mm, it was found that the highest strain rate produces distinct regimes of mechanical response as shown in Fig. 2. The flow stress for compression done at high strain rate ( $10 \text{ sec}^{-1}$ ) showed sharp increase of flow stress at very low strain and was followed by a plateau of relatively constant flow stress and almost no work hardening. On the other hand, specimens compressing at low strain rate ( $0.1 \text{ sec}^{-1}$ ) showed sustained work hardening response up to the strain level 0.2 for both aluminum and titanium materials. In general, loading at higher strain rate produces higher flow stress response and reduced ductility, and this strain rate effect is especially significant at high temperature. However, there have been reported results on the softening behavior in high strain rate loading at room temperature such as one presented by Hoge and Mukherjee (1977) and dislocation drag was proposed to explain the behavior.

In contrast with specimen diameter 0.5 mm, there is no significant influence of strain rate on the compression for both materials as presented in Fig. 3. This suggests that either the dislocation drag mechanism gets weaker with miniaturization or that there is a competing mechanism which cancels out the effect of dislocation drag. In order to conclude the explanation for the non-sensitivity of strain rate at 0.5 mm, further experiments should be considered to cover wider range of specimen size including those smaller than 0.5 mm and with smaller size increments.

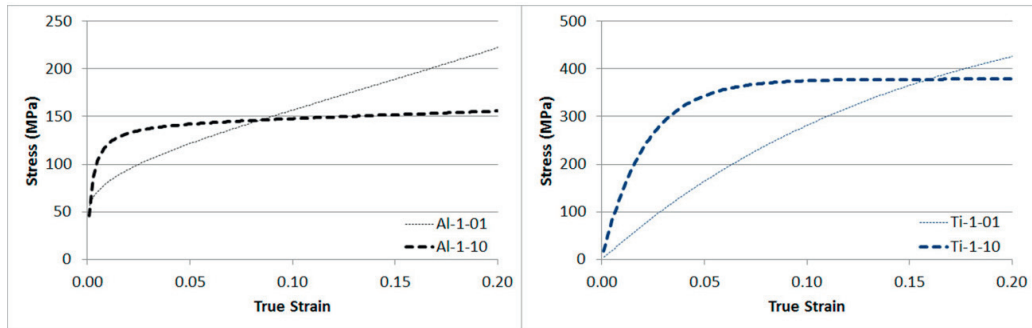


Fig. 2. Hardening and softening competition at different strain rates (Specimen diameter 1 mm).

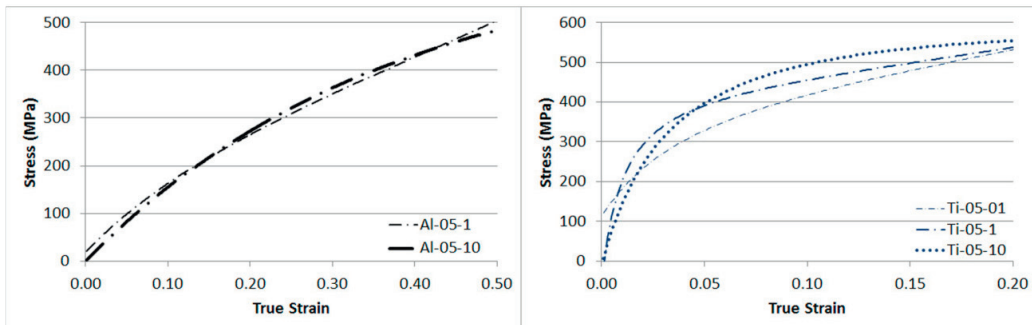


Fig. 3. Hardening and softening competition at different strain rates (Specimen diameter 0.5 mm).

A different perspective for explaining this behavior can be taken by analyzing the mechanical response during compression at various specimen sizes at a specific strain rate. At strain rate  $0.1 \text{ sec}^{-1}$ , it was found that flow stress throughout all measured strain decreases with miniaturization. This observation was consistent for both materials as presented in Fig. 4. This result is in agreement with the surface layer model from Geiger et al. (2001) albeit with much stronger influence. The surface layer model was proposed following compression experiment with very low strain rate ( $< 0.01 \text{ sec}^{-1}$ ). However, when the strain rate is significantly increased to  $10 \text{ sec}^{-1}$ , although at low strain they showed lower flow stress, the smallest specimens in the test showed much stronger work hardening as shown in Fig. 5. As the specimen compresses, free surface grains gradually transform into constrained surface grain as the height of the specimen decreases and its contact area with the tool increases. Therefore the strengthening effect from constrained surface grains becomes stronger.

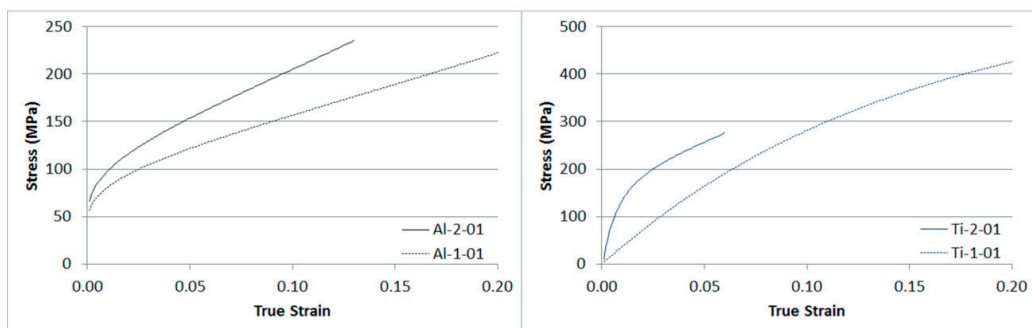


Fig. 4. Flow stress decreases with miniaturization (strain rate  $0.1 \text{ sec}^{-1}$ ).

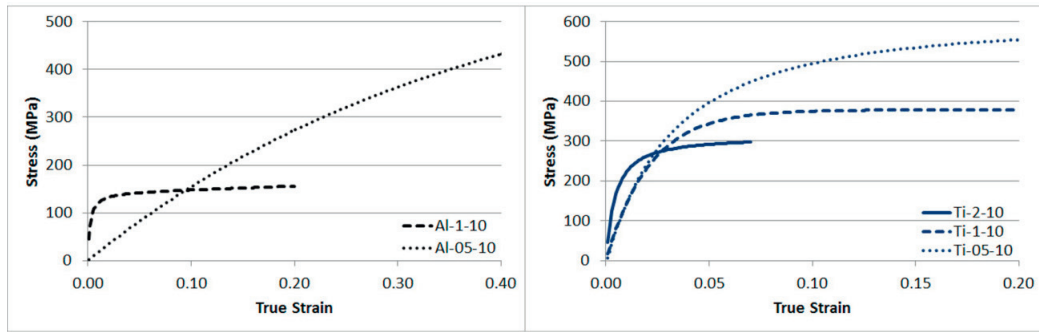


Fig. 5. Hardening is strengthened with miniaturization (strain rate  $10 \text{ sec}^{-1}$ ).

## 5. Concluding remark

The effect of strain rate and specimen size on the flow stress during a micro compression experiment was investigated for aluminum and titanium. Despite their different crystal structures, both materials showed compounding effects on the material response during compression. With specimen diameter 1 mm, deformation at high strain rate of  $10 \text{ sec}^{-1}$  produces sharp flow stress increase at low strain followed by insignificant work hardening. On the other hand, lower compression strain rate results in more sustained work hardening response, producing a hardening-softening competition. Meanwhile in the compression experiment with 0.5 mm diameter specimens, there is no visible effect of strain rates on flow stress. In order to systematically determine these hardening and softening effects of strain rates, further experimentation is proposed with more specimen sizes between 2 and 0.5 mm as well as with specimens smaller than 0.5 mm.

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